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Manufacturability of high power ultraviolet-C light emitting diodes on bulk aluminum nitride substrates

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ABSTRACT

As the technological challenges in obtaining high power ultraviolet-C light emitting diodes (LEDs) on bulk AlN substrates are being overcome, the next challenge faced is the manufacturability. One of these challenges consists of introducing a 10 × 10 mm substrate into a fabrication facility that is processing 2" and larger diameter substrates. This has been successfully carried out using a standard visible LED production facility that is involved in high volume manufacturing of blue LEDs. By introducing specifications on the substrates, the epitaxial wafers, and the fabrication process, the establishment of a pilot production process with pathways to high volume manufacturing has been established.

1. Introduction

Ultraviolet-C light emitting diodes (UVC LEDs) are proving to be very useful for disinfection applications [1,2] and for biological detection applications [3]. The output powers and efficiencies of these devices are steadily increasing and are beginning to reach values where they will be able to be used in commercial products and not just as laboratory demonstrations. However several issues remain in order to replace the existing mercury bulbs in many applications, including disinfection applications. The UVC LEDs have the inherent advantages of small size, ruggedness, and instant turn on ability. The radiance of these small LEDs already exceeds that of mercury lamps while the efficiency is expected to surpass in the future. However, cost and manufacturability are also significant barriers to widespread adaptation of these UVC LEDs. The ability to use the same processing equipment used for blue LEDs will have tremendous advantages for increasing availability and reducing costs once the substrate and epitaxial growth processes are improved.

Bulk AlN substrates are an ideal solution for the growth of UVC LEDs. They are optically transparent at this wavelength, although impurities can lead to absorption. Bulk AlN substrates are also closely lattice and thermally expansion matched to the layers required for the device structure. In addition, pseudomorphic growth can be achieved allowing for low dislocation density in the active region of the device [4]. This approach has been used to achieve the best efficiency and output power [5], as well as lifetime [6], in the 265 nm wavelength range. However, currently these substrates are only available in limited quantities and sizes preventing large scale manufacturing such as is occurring with visible LEDs. Regardless, we have succeeded in setting up pilot production of UVC LEDs to enable low volume manufacturing and allow for rapid increase in volumes as supply and size of the AlN substrates are increased. In this paper, the epitaxial growth process and fabrication process will be described in terms of manufacturability.

2. Epitaxial growth and device fabrication

The substrate fabrication and epitaxial growth is carried out at the Crystal IS facility in Green Island, NY. A set of specifications have been developed for substrate fabrication to ensure that each substrate will be capable of producing high quality UVC LEDs. This includes the optical transparency, surface miscut, as well as crystal quality. Each substrate is 10 × 10 mm in size. After validating that the substrate meets the minimum specifications, epitaxial growth is carried out. The epitaxial growth is completed in a Veeco D180 MOCVD reactor. Again, a set of specifications has been defined to ensure that the epitaxial growth is of suitable quality and meets necessary criteria to obtain high quality UVC LEDs. After the epitaxial growth and characterization is completed, the wafers are kitted into a fabrication lot and submitted for fabrication.

The device fabrication is carried out at Sanan Optoelectronics using equipment and processes developed for the high volume manufacture of visible LEDs on sapphire substrates with few minor changes required for the UVC LEDs. First, the mesa is defined using photolithography and etched in an Inductively Coupled Plasma tool. This etch is followed by *n*-metal deposition, *p*-metal deposi-

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tion, and finally pad metal deposition. At this point the on wafer testing is carried out to provide details of the device performance. The toolset for this fabrication process consists of processing equipment such as mask aligner; ion-coupled plasma etcher; e-beam metal deposition chamber; rapid thermal processor and annealing furnace. Processing monitors for each critical process have been incorporated into the individual mask set to monitor processing variance and to establish a data base to determine processing tolerance. Circular transmittance line monitors (CTLMs) have been included to measure contact resistance of the *p* and *n* metal contacts of the UVC LED. In addition, a tentative product management plan (PMP) has also established to track the individual processing steps for cost analysis and for yield parameter control.

3. Results and discussion

3.1. Epitaxial growth

The epitaxial structure is grown as described previously [7]. The epitaxial growth process is tracked using both noncontact sheet resistance measurements and X-ray diffraction for analyzing the variation in aluminum content of the *n* type AlGaN layer of each wafer. The sheet resistance and Al content over 20 fabrication lots is shown in Fig. 1. This figure contains a variability chart grouped by lot number and a distribution of all lots fitted with a normal distribution. Each point on the variability chart represents the sheet resistance of the wafer. The chart also contains range bars, cell means, and box plots for each lot. The range bars show the maximum and the minimum sheet resistance in each lot with a bar for the cell mean. The box plot represents the quartiles along with the median value. The distribution shows the data for all lots with the *x*-axis representing counts for each bin range shown on the *y*-axis. The line is the fitted normal distribution represented by a mean and dispersion. An outlier box plot is also shown for the distribution. This contains a box showing quartiles and median value along with a mean diamond showing the mean value and 95% confidence interval for the mean. The whiskers extending from the box represent the outer most data point which is within 50% of the interquartile range. Any data points outside this range are shown on the plot as outliers. There is also a bracket showing the shortest half which is the densest 50% of the data points. The sheet resistance shows a normal distribution with a mean of 341 Ω/sq. and dispersion of 89 Ω/sq. This value is desired to be as low as possible but the current range is more than adequate for high performance UVCLEDs. An upper specification limit of 1000 has been chosen as the limit for submitting wafers for fabrication. The Al content is targeted at 70% with an upper specification limit (USL) of 75% and a lower specification limit (LSL) of 65%. These specification limits are shown as a dotted line on the variability chart. The distribution is bimodal but does have a mean value of 70.0% and a dispersion of 2.2% indicating the Al% is well controlled with the specification limits. In addition the pseudomorphic nature of the layers is tracked using X-ray diffraction to measure the strain within each sample. The sample must be fully strained within measurement error to be submitted for fabrication.

3.2. Fabrication process

The fabrication process is similar to high volume production of visible LEDs but differs in several key areas. As fabrication facilities are moving beyond 2" substrates and relying on more sophisticated automation to improve yields, the processing of 10 × 10 mm substrates presents challenges in wafer handling and processing. We have been successful in implementing the fabrication of these wafers in pilot production. By carefully tracking key process

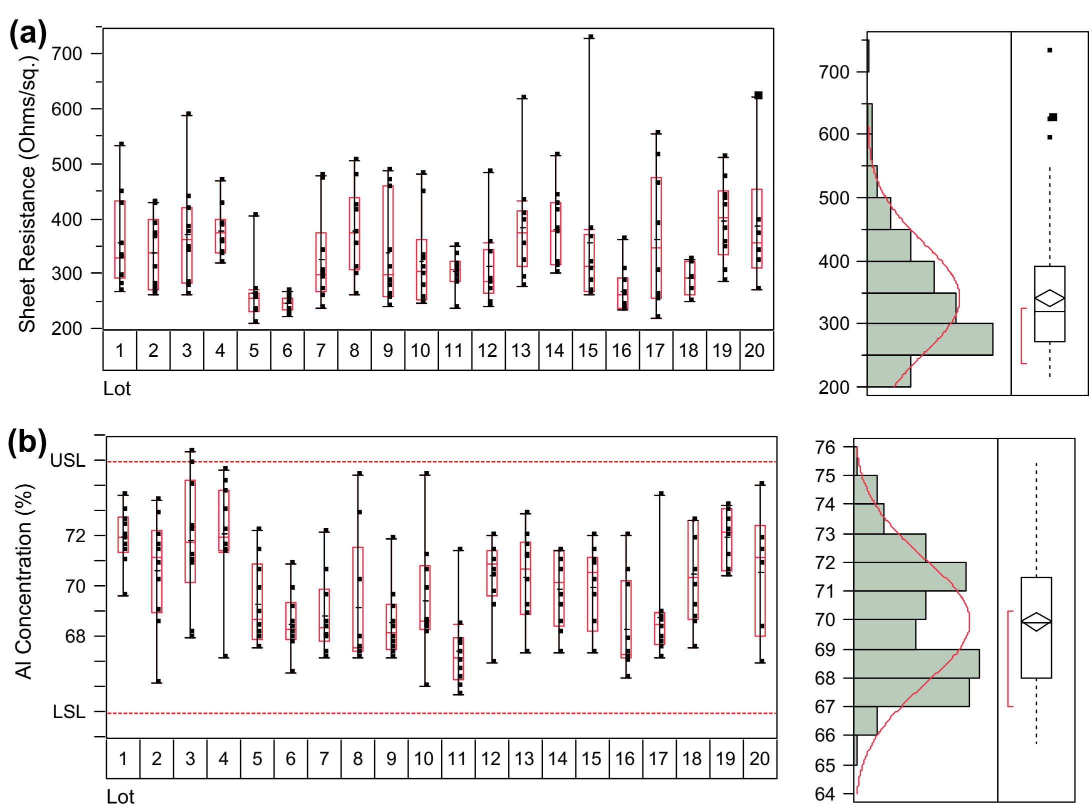

Fig. 1. Variability charts and distribution for (a) sheet resistance and (b) Al composition of epitaxial wafers fabricated in the pilot production process.